ABC–62
ESG Tech Note 186

ASSESSMENT OF THE BEAM-BEAM EFFECT FOR VARIOUS OPERATING SCENARIOS IN APIARY 6.3–D

Jennifer R. Eden and Miguel A. Furman

LBL/ESG

May 1992 (minor corrections: 3/3/04)

ABSTRACT

We consider the beam-beam interaction for the APIARY 6.3–D design of the SLAC/LBL/LLNL B factory for a variety of conditions, for a fixed working point just above the half-integer. We focus primarily on the effect of the collisions at the parasitic crossing (PC) points. Our studies are based on multiparticle tracking simulations with Tennyson's code TRS. We conclude that bunch spacing is the variable with the most obvious effect on reliability for a given specification of nominal luminosity. In most cases we can also conclude that running the simulations for three damping times is sufficient to observe the equilibrium state, at least for $\xi_0 = 0.03$. A certain "universality" suggests itself: the curves that describe beam blowup vs. normalized PC separation seem to depend on fewer parameters than they in principle could. Scaling rules can thereby be conjectured. Further studies are needed in order to confirm this universality.

1. Introduction

We present a comparative assessment of the short-time-average luminosity performance of the proposed B factory design[1] APIARY 6.3–D by varying certain beam-beam-related parameters under certain assumptions, listed in Sec. 2. Although the design of the interaction region (IR) has been recently updated,[2] we believe that our conclusions remain qualitatively valid for purposes of relative comparisons. A detailed study along the lines presented here for the updated design will be presented separately.

Essentially all of the results presented here (and in the CDR[1]) show that, if it were not for the effect of the parasitic collisions, the APIARY 6.3–D design would be quite conservative from the point of view of the beam-beam interaction, provided a suitable working point is chosen. This conclusion seems to hold true even when the bunch current is higher than nominal, corresponding to a beam-beam parameter $\xi_0 = 0.05$ rather than to its nominal specification of 0.03. Depending on the value of other parameters, however, the parasitic collisions can induce substantial beam blowup in certain cases that can render the design less conservative. For this reason the main focus of this comparative assessment is whether the parasitic collisions occur far enough apart that they are effectively harmless. Thus the fundamental variable we have chosen in our comparisons is the separation d between the nominal orbits of the two beams at the first parasitic crossing (PC) point. In the limit where $d \to \infty$ all effects of the PCs disappear, and only those effects from the primary collisions at the interaction point (IP) remain. Our main goal, then, is to assess the relative effects of the PC collisions in several cases. The nominal specification for APIARY 6.3–D is $d = 2.82$ mm; in the updated[2] IR design (APIARY 7.5) the specification is $d = 3.498$ mm. In keeping with our adopted strategy, however, we take d to be a free parameter that we vary independently of all others.

All the results presented here are in the form of plots of beam blowup factors σ/σ_0 *vs.* $d/\sigma_{0x,+}$. This latter variable is the PC separation in units of the local nominal horizontal beam size of the LER. The nominal APIARY 6.3–D design implies a value $d/\sigma_{0x,+} = 7.57$. However, as mentioned above, in our simulations we vary $d/\sigma_{0x,+}$ by varying d while keeping all other parameters fixed. The calculations were carried out with Tennyson's code TRS[3] mostly on the San Diego Supercomputer Center's CRAY Y-MP. In most cases we have looked at the two by-now customary values for the nominal beam-beam parameter, namely $\xi_0 = 0.03$ and $\xi_0 = 0.05$ (all four nominal ξ-parameters are set equal). In all cases the positron beam energy is 3.1 GeV and the electron beam energy is 9.0 GeV, and the fractional parts of the tunes are $(\nu_x, \nu_y) = (0.64, 0.57)$ for both beams.

Although the predictions of the code compare favorably with certain experimental results,[1] the simulations invoke many simplifying assumptions. For example, we neglect all lattice nonlinearites in the model for the machine. However, we are concerned only with the short-time-average luminosity performance, so that we study only the behavior of the core of the beam. It is reasonable, therefore, to assume that machine nonlinearities are not very important for our purposes. Nevertheless, until more detailed and complete studies are carried out, it is prudent to assume that the relative predictions from our simulations are more reliable than the absolute predictions for any individual case.

We present 12 study cases, which we call "1A," "1B," etc. A detailed explanation of the parameters used in each case is presented in Sec. 3. For now, suffice it to say that the cases are distinguished by differences in the following parameters: the nominal beam-beam parameter ξ_0, the damping times $\tau_\pm$, the number of particles per bunch $N_\pm$ and the bunch spacing s_B. In addition, we have also varied the following parameters in the simulations: the number of "superparticles" used to describe the beam, the number of slices into which the bunch is divided longitudinally, and the number of turns for which the tracking program is run. These parameters are not varied independently; the details are explained in Sec. 3.

In addition to these 12 cases, we present, for reference, two additional cases, which we call cases "0A" and "0B." Case 0A is the corrected version of the CDR's nominal case, shown in Fig. 4-91(a) of the CDR.[1] Case 0B corresponds exactly to the one shown in the CDR's Fig. 4-91(b). The corresponding parameters are stated in Sec. 3.

2. Assumptions

All basic nominal parameters are listed in tables 1A, 1B, 2A, 2B, 3A and 3B below. The values of the parameters used in each case are listed in these tables, with a few variants in some cases. The precise description of all study cases is stated in Sec. 3. Here is a summary of the assumptions we have made:

2.1 IR lattice

We have assumed the nominal[1] APIARY 6.3–D lattice parameters for the IR. The working point is the same for all 12 cases, namely $(\nu_x, \nu_y) = (0.64, 0.57)$ for both beams. These are the "bare machine" tunes, *i.e.*, in the absence of the beam-beam interaction. For cases in which $\xi_0 = 0.03$, a particle at the center of the bunch experiences tunes that are displaced approximately by +0.03 in both ν_x and ν_y from the working point. The beta functions at the interaction point and other nominal parameters are listed in the tables below. The RF wavelength, λ_{RF}, is 0.6298 m in all cases. We consider two values for the bunch spacing, namely the nominal $s_B = 2\lambda_{RF} = 1.2596$ m (cases 1A, 1A2, 1B, 1B2, 5A, 6A and 6B) and the alternative value $s_B = 3\lambda_{RF} = 1.8894$ m (cases 2A, 2A2, 2B, 3A and 3B). If the bunch spacing is $2\lambda_{RF}$, the nominal closed orbit separation at the PC is $d = 2.82$ mm; if the bunch spacing is $3\lambda_{RF}$, it is $d = 7.41$ mm. The lattice functions at the corresponding PC points are listed in the tables. We do not take into account any PCs beyond the first one on either side of the IP because these "outer" PCs are very weak relative to the first one.

2.2 Primary beam-related parameters

Full beam-beam transparency symmetry[4] is assumed; thus the rms beam sizes at the IP are pairwise equal, and all four nominal beam-beam parameters ξ_0 are equal. The values we have chosen are $\xi_0 = 0.03$ (cases "A") and $\xi_0 = 0.05$ (cases "B"). In going from a given case "A" to the corresponding case "B" we have increased the number of particles per bunch by a factor of 5/3 at fixed emittance. Therefore, the nominal luminosity $\mathscr{L}_0$ is larger by a factor $(5/3)^2$ in case "B" than in the corresponding case "A." The actual values of $\mathscr{L}_0$ in each case are stated below.

2.3 Other parameters

The number of particles per bunch, nominal emittances, rms beam sizes and rms angular divergences at the collision points are determined by the lattice functions, collision frequency, and the primary parameters ξ_0 and $\mathscr{L}_0$. These are all listed in the tables. The bunch length σ_ℓ, rms energy spread σ_E/E and synchrotron tune ν_s are different for the two beams, but are held fixed at their specified CDR values throughout our studies.

2.4 Simulation details

In all cases we have chosen 256 "superparticles" per bunch that are Gaussian-distributed in the six-dimensional phase space at the initial step in the simulation. As time progresses, the distribution deviates from Gaussian at least to some extent; nevertheless, for the purposes of calculating the beam-beam kick, we compute at every turn the rms sizes and centers of the distribution, from which the beam-beam force is determined from a well-known formula.[5] Thick lens effects[6] during the collision are taken into account by dividing up the bunch longitudinally into either three or five slices. In those cases in which we use three slices, these are located at $z = 0$ and $\pm\sigma_\ell$. For five slices, the locations are $z = 0$, $\pm(7/12)\sigma_\ell$, and $\pm(7/6)\sigma_\ell$. Depending on the particular case, the simulations are run for either three or five damping times. Usually the beam sizes settle to a stable value by three damping times; the actual beam sizes are then calculated by averaging over the stable values. Radiation damping and quantum excitaqtion, as well as synchrotron oscillations, are included in the simulation. The arc between the IP and the PC is represented by a linear transport matrix whose phase advance is specified in the tables below. The arc between one PC and the next PC (the region "outside" the IR) is also assumed to be linear; its phase advance is the balance of the tune of the machine.

The beams collide head-on at the IP and are then magnetically separated in the horizontal plane. In the APIARY 6.3-D design the bunches go into their separate vacuum pipes only after traveling about 4 m away from the IP; as a result, they experience several grazing collisions on their way into and out of the IP. There are six such "parasitic crossings" on either side of the IP in this IR design. These PCs couple the dynamics of all bunches, so that a completely faithful simulation of the beam-beam dynamics would require 1658 bunches per ring, along with a gap equivalent to 88 bunches. Since this is an impractical requirement for any present-day simulation, we have made two simplifying approximations: (i) we consider only the first PC on either side of the IP, and (ii) we use only one bunch per ring, which is "re-used" so that this bunch collides three times per turn – two PCs plus the primary collision at IP – with the same partner in the other beam. The first approximation is quite reasonable because the first PC overwhelms all the others[1] (the first PC is separated from the IP by the beam separator dipole magnet; the remaining PCs are separated from the first one by quadrupole magnets). The second approximation rests on the sensible assumption that, in reality (or in a faithful simulation), the particle distributions will not differ much from bunch to bunch, especially when seen at a distance, as is the case at the PCs. Stated in more technical terms, we are assuming that the coherent dipole modes of the beams are effectively decoupled from the quadrupole modes, and that the quadrupole modes are weakly coupled from bunch to bunch. Although we cannot verify the validity of these assumptions within the scope of our approximations, at least we have monitored our results, to the extent that is possible, for consistency with the assumptions.

3. Details of study cases

Table 4 provides a summary of the parameters used for all 12 simulation cases. Here we provide a detailed case-by-case explanation:

3.1 Case 0A (Figs. 1 and 2)

This case is the one shown in Fig. 4-91(a) of the CDR,[1] corrected for an error. We call this the "old nominal CDR" case, corresponding to the old working point. The parameters are listed in Table 1A, except that the tunes have the old values $(\nu_x, \nu_y) = (0.09, 0.05)$ for both beams. This case has $\xi_0 = 0.03$ and $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}. The simulation was run for 15,000 turns, or about three damping times, with 128 superparticles per bunch divided up longitudinally into three slices.

3.2 Case 0B (Fig. 3)

This is the "high-current" version of case 0A. It is shown in Fig. 4-91(b) of the CDR. The parameters are listed in Table 1B, except that the tunes are (0.09, 0.05) for both beams. In this case ξ_0=0.05 and $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}. The higher value for ξ_0 is achieved by increasing $N_\pm$ by a factor of 5/3 from case 0A, keeping the nominal emittances fixed. The simulation was run for 15,000 turns, with 128 superparticles per bunch divided up longitudinally into three slices.

3.3 Case 1A (Fig. 4)

We call this the "nominal CDR" case. The parameters are listed in Table 1A. This case has $\xi_0 = 0.03$ and $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}. The only difference with the "old nominal CDR" case is the working point, which, as mentioned above, is now taken to be $(\nu_x, \nu_y) = (0.64, 0.57)$ for both beams. The same working point is used in all subsequent cases presented here. The simulation was run for 15,000 turns, with 256 superparticles per bunch divided up longitudinally into three slices.

3.4 Case 1A2 (Fig. 5)

Same as case 1A except that the damping times (horizontal and vertical) are exactly equal for both beams. The parameters are those in Table 1A except that the damping times are $\tau_+ = \tau_- = 5{,}014$ turns. The simulation was run for 15,000 turns, with 256 superparticles per bunch divided up longitudinally into three slices.

3.5 Case 1B (Fig. 6)

This is the high-current version of case 1A, except that the number of superparticles used in this case was 128. The full set of parameters is listed in Table 1B. In this case $\xi_0 = 0.05$ and $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}. As in case 0B, the higher value for ξ_0 is achieved by increasing $N_\pm$ by a factor of 5/3 from case 1A, keeping the nominal emittances fixed. The simulation was run for 15,000 turns, with the bunch divided up longitudinally into three slices.

3.6 Case 1B2 (Fig. 7)

This is the same as case 1B except that we used 256 superparticles per bunch.

3.7 Case 2A (Fig. 8)

In this case the bunch spacing is 50% larger than in case 1A, namely $s_B = 3\lambda_{RF} =$ 1.89 m. The motivation for this increase is the desire to weaken the effect of the parasitic collisions: in this case the first PC occurs at a distance Δs = 94.47 cm from the IP, where the nominal orbit separation is 7.41 mm instead of 2.82 mm. Because the bunch collision frequency is down by a factor of 1.5 relative to case 1A, the nominal luminosity would decrease by the same factor if the bunch currents and sizes were left unchanged. In order to keep ξ_0 and $\mathscr{L}_0$ at their nominal values of 0.03 and 3×10^{33} cm^{-2} s^{-1}, respectively, we have increased the number of particles per bunch $N_\pm$ and the four emittances ε_0 by 50% relative to case 1A; we call these "fat bunches" (the total beam current remains unchanged relative to case 1A). All parameters are listed in Table 2A, which reflects these changes. The simulation was run for 15,000 turns, with 128 superparticles per bunch divided up longitudinally into three slices.

3.8 Case 2A2 (Fig. 9)

This is the same as case 2A except that we used 256 superparticles per bunch.

3.9 Case 2B (Fig. 10)

This is the high-current version of case 2A2. The full set of parameters is listed in Table 2B. In this case $\xi_0 = 0.05$ and $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}. As before, the higher value for ξ_0 is achieved by increasing $N_\pm$ by a factor of 5/3 from case 2A, keeping the nominal emittances fixed. The simulation was run for 15,000 turns, with 256 superparticles per bunch divided up longitudinally into three slices.

3.10 Case 3A (Fig. 11)

This is an intermediate case between 1A and 2A: the bunch currents and emittances are as in case 1A, but the bunch spacing is $s_B = 3\lambda_{RF} = 1.89$ m. Thus $\xi_0 = 0.03$, but the nominal luminosity is only 2/3 of case 1A, namely $\mathscr{L}_0 = 2 \times 10^{33}$ cm^{-2} s^{-1}. The full set of parameters is listed in Table 3A. The simulation was run for 15,000 turns, with 256 superparticles per bunch divided up longitudinally into three slices.

3.11 Case 3B (Fig. 12)

This is the high-current version of case 3A, with $\xi_0 = 0.05$. The higher value for ξ_0 is achieved by increasing $N_\pm$ by a factor of 5/3 from case 3A at fixed nominal emittances. The resultant luminosity is a factor $(5/3)^2$ larger than in case 3A, namely $\mathscr{L}_0 = 5.56 \times 10^{33}$ cm^{-2} s^{-1}. The full set of parameters is listed in Table 3B. The simulation was run for 15,000 turns, with 256 superparticles per bunch divided up longitudinally into three slices.

3.12 Case 5A (Fig. 13)

This is the same as case 1A2 except that the LER damping time is doubled, namely $\tau_{x+} = \tau_{y+} =$ 10,028 turns. The parameters are listed in Table 1A, except for these changes.

The HER damping time is the same as in case 1A, namely $\tau_{x-} = \tau_{y-} = 5{,}014$ turns. The simulation was run for 30,000 turns, or about three LER damping times, with 256 superparticles per bunch divided up longitudinally into three slices. The simulation was "weak-strong," in which the HER bunch sizes were held fixed at their nominal values throughout the simulation. We carried out one spot check with a strong-strong simulation for the nominal value of the PC orbit separation, $d = 2.82$ mm.

3.13 Case 6A (Fig. 14)

Same as case 1A2 (horizontal and vertical damping times are the same for both rings, $\tau_+ = \tau_- = 5{,}014$ turns), except that the simulation was run for 25,000 turns, or about five damping times, with 256 superparticles per bunch divided up longitudinally into five slices. The parameters are listed in Table 1A, except for these changes in the values of the damping times.

3.14 Case 6B (Fig. 15)

High-current version of case 6A, with $\xi_0 = 0.05$ and $\mathcal{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}. As before, the higher value for ξ_0 is achieved by increasing $N_\pm$ by a factor of 5/3 from case 6A, keeping the nominal emittances fixed. The simulation was run for 25,000 turns, or about five damping times, with 256 superparticles per bunch divided up longitudinally into five slices. The parameters are listed in Table 1B, except for the changes in the values of the damping times mentioned in Case 6A.

4. Discussion of results

We now compare the results for these 12 cases, shown in the plots for the beam blowup factors σ/σ_0 *vs.* $d/\sigma_{0x,+}$. As mentioned above, in these plots we vary d while keeping all other parameters fixed.

4.1 Old vs. new working points (0A vs. 1A and 0B vs. 1B2)

By comparing cases 0A with 1A (Fig. 16) one can see that the onset of large beam blowup as $d \to 0$ is closer to the nominal PC separation for the old working point. Thus the new working point provides a larger margin of comfort. As $d \to \infty$ the effect of the PCs disappear, and the remaining blowup is due exclusively to the primary collisions at the IP. This asymptotic value for the blowup factor is larger for the new working point than for the old one, and it has been sensibly reached for the nominal value of d in case 1A but not in case 0A. For the nominal value of d, the blowup factor for the LEB in the vertical direction, ~30%, is the same for the new working point as it is for the old working point. This results in a small degradation of the luminosity from its nominal value, yielding a dynamical value $\mathcal{L}$~2.6×10^{33} cm^{-2} s^{-1} for both cases 0A and 1A.

Qualitatively similar remarks apply to the high-current ($\xi_0 = 0.05$) cases 0B and 1B2 (Fig. 17). For the old working point the LEB's vertical blowup factor is ~ 3, while it is

~ 2 for the new working point. This blowup results in a substantial reduction of the luminosity relative to its nominal value; however, since the nominal value in this case is 8.33 × 10^{33} cm^{-2} s^{-1}, the resultant *absolute* dynamical value for case 1B is still quite high, $\mathcal{L}$ ~ 5.3 × 10^{33} cm^{-2} s^{-1}. For case 0B, the larger blowup brings the dynamical luminosity down to ~3 × 10^{33} cm^{-2} s^{-1}, which shows that, for the old working point, the increase in bunch current is essentially ineffective in increasing the luminosity performance. In other words, the luminosity has reached saturation as a function of bunch current, and the beam-beam limit has already been reached at the nominal specification $\xi_0 = 0.03$.

In case 1B2 one can also see that the beams go into a "flip-flop" configuration for $d/\sigma_{0x,+} \lesssim 5$, in which the HEB is essentially of nominal size while the LEB is blown up substantially in the vertical dimension. Due to the nature of the approximations we are making, we are not certain that this is a realistic prediction because in this case the PC collisions are effectively strong; in any case, this result indicates that it seems prudent to stay away from possible IR designs in which d is too small.

4.2 Approximately equal vs. exactly equal damping times (1A vs. 1A2)

We have done most of the beam-beam simulations presented here and in Sec. 4.4 of the CDR with $\tau_+ = 4400$ turns and $\tau_- = 5014$ turns, in spite of the fact that the nominal APIARY 6.3–D design, described in other sections of the CDR, specifies $\tau_+ = \tau_- = 5014$ turns (with $\tau_x = \tau_y$ for either ring). The discrepancy is a result of historical reasons: we began the beam-beam calculations before the lattice details were finalized, and kept the initial values unchanged despite subsequent lattice developments.

Comparing cases 1A and 1A2 (Fig. 18), one can see that there is no significant difference between these two cases, at least for $d \geq$ nominal value; thus the dynamical value of the luminosity for case 1A2 for d = nominal is $\mathcal{L}$ ~ 2.6 × 10^{33} cm^{-2} s^{-1}. The different behavior in the two cases for small values of d is interesting, but this is of no immediate concern to us. From this comparison we may conclude that the simulation results with $\tau_+ = 4400$ turns are valid predictors for the nominal case with $\tau_+ = 5014$ turns, at least for $\xi_0 = 0.03$.

4.3 Three slices and short runs vs. five slices and long runs (1A2 vs. 6A and 1B2 vs. 6B)

In comparing cases 1A2 with 6A (Fig. 19) one can see that there is no qualitative difference. The dip in the blowup factors in case 1A2 for $d/\sigma_{0x,+} \approx 6$ has disappeared in the more accurate calculation of case 6A. In any case, the "short-cut" calculation 1A2 seems to be a reliable predictor of beam blowup for $d \geq$ nominal value for $\xi_0 = 0.03$. The dynamical luminosity for case 6A is $\mathcal{L}$ ~ 2.6 × 10^{33} cm^{-2} s^{-1}.

Similar conclusions apply when comparing the corresponding high-current ($\xi_0 = 0.05$) cases 1B2 and 6B (Fig. 20). Actually, this particular comparison skips one step because case 1B2 has $\tau_+ = 4400$ turns, whereas 6B has $\tau_+ = 5014$ turns. We are assuming that, for $\xi_0 = 0.05$, there are no significant differences when going from $\tau_+ = 4400$ turns to

τ_+ = 5014 turns with all other parameters fixed. The dynamical luminosity in both cases 1B2 and 6B is $\mathscr{L} \sim 5.3 \times 10^{33}$ cm^{-2} s^{-1}.

4.4 τ_+ = 5014 turns vs. τ_+ = 10028 turns (1A2 vs. 5A)

The value of the LER damping time, τ_+ = 5014 turns, assumes the use of wigglers; the natural damping time is substantially longer than this. It would be advantageous to reduce the strength of the wigglers or to dispense with them altogether. This would result in very different damping times for the two rings. Case 5A, with τ_+ = 10028 turns, represents one step in this direction. In this case three damping times means ~30000 turns, so the simulation is quite expensive. In order to get a first impression, we have therefore carried out a less expensive weak-strong simulation, in which the HEB sizes are held fixed while the LEB is allowed to evolve dynamically. We have carried out one strong-strong spot-check for the nominal value of d. In this spot-check only the vertical blowup of the LER, $\sigma_{y,+}/\sigma_{0y,+}$, is significantly different from the weak-strong results. In comparing cases 1A2 with 5A (Fig. 21) one can see that there is no qualitative difference for $d/\sigma_{0x,+} \gtrsim 6$. The dynamical luminosity for case 5A is $\mathscr{L} \sim 2.7 \times 10^{33}$ cm^{-2} s^{-1}, which is essentially the same as in cases 1A2 and 1A. It seems, therefore, that longer damping times are possible for the LER without significant adverse effects on the beam blowup and luminosity performance, at least for ξ_0 = 0.03. This conclusion, however, needs to be tested with more simulations, over a larger range of parameter values. In particular, we do not yet have any indication whether it is true for higher values of ξ_0.

4.5 $s_B = 2\lambda_{RF}$ vs. $s_B = 3\lambda_{RF}$ (1A vs. 2A2 and 1B2 vs. 2B)

The motivation for increasing the bunch spacing is to try to weaken the effect of the PCs even further, should the need arise. In all cases “2” the normalized PC separation is $d/\sigma_{0x,+}$ = 9.17 rather than 7.57 for cases “0” and “1.” As explained before, the price to be paid is a 50% increase in the bunch current plus a 50% increase in the nominal emittances of both beams (“fat bunches”). Comparing the blowup plots for cases 1A and 2A2 (Fig. 22), one can see that the curves themselves have quite similar behavior: in both cases the onset of substantial beam blowup happens for a “threshold” $d/\sigma_{0x,+} \lesssim 6$. The advantage of case 2A2 over 1A is the increased spacing between the actual value of $d/\sigma_{0x,+}$ and the threshold for the onset of significant blowup. This provides a greater margin of comfort in case 2A2, although the actual blowup is quite similar in both cases, yielding a dynamical luminosity $\mathscr{L} \sim 2.7 \times 10^{33}$ cm^{-2} s^{-1} in case 2A2.

Qualitatively similar conclusions apply when comparing the corresponding high-current cases 1B2 and 2B (Fig. 23). However, the blowup is smaller in 2B than in 1B2, yielding a dynamical luminosity $\mathscr{L} \sim 6.5 \times 10^{33}$ cm^{-2} s^{-1} for 2B and $\sim 5.3 \times 10^{33}$ cm^{-2} s^{-1} in 1B2.

4.6 "Fat" bunches vs. nominal bunches (2A2 vs. 3A and 2B vs. 3B)

All cases "2" and "3" have a bunch spacing $s_B = 3\lambda_{RF} = 1.89$ m; the difference is that in cases "2" the bunches are fat (see previous paragraph), whereas in cases "3" the bunch parameters are the same as in the respective cases "1." In cases 3A and 3B the normalized PC separation is $d/\sigma_{0x,+} = 11.2$, which is even more comfortable than the 9.17 value in cases "2." As before, when comparing the plots for cases 2A2 and 3A (Fig. 24), one sees that the curves themselves are similar; the advantage of 3A over 2A2 is the increased safety margin. The price for this increase is paid in luminosity, whose nominal value is $\mathscr{L}_0 = 2 \times 10^{33}$ cm^{-2} s^{-1} rather than 3×10^{33} cm^{-2} s^{-1} in cases 1A, 1A2, 2A and 2A2. However, the dynamical luminosities are closer to each other than their nominal counterparts, with $\mathscr{L} \sim 1.9 \times 10^{33}$ cm^{-2} s^{-1} for 3A and $\mathscr{L} \sim 2.7 \times 10^{33}$ cm^{-2} s^{-1} for 2A2.

Qualitatively similar remarks apply when comparing the corresponding high-current cases 2B and 3B (Fig. 25): case 3B has a greater safety margin than 2B, although the nominal luminosities are different, $\mathscr{L}_0 = 5.56 \times 10^{33}$ cm^{-2} s^{-1} for case 3B and $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1} for case 2B. Because of the different amounts of beam blowup, however, the dynamical values for the luminosity are closer to each other, $\mathscr{L} \sim 4.4 \times 10^{33}$ cm^{-2} s^{-1} and $\mathscr{L} \sim 6.5 \times 10^{33}$ cm^{-2} s^{-1}, respectively.

4.7 256 vs. 128 superparticles per bunch (2A2 vs. 2A and 1B2 vs. 1B)

In comparing cases 2A2 with 2A ($\xi_0 = 0.03$) one sees (Fig. 26) that the blowup curves are quite similar for $d/\sigma_{0x,+} \gtrsim 5$, so that the predictions of the short-cut calculation 2A seem to be reliable for the relevant values of $d/\sigma_{0x,+}$. In comparing 1B2 with 1B ($\xi_0 = 0.05$) one sees (Fig. 27) that the agreement is only qualitative, although the actual value of the beam blowup factor is the same in both cases.

5. Conclusions

(1) The vertical size of the LEB tends to blow up the most. This is probably due to the large value of $\beta_{y,+}$ at the PC location. Since $\beta_{y,+}$ is the smallest of the four beta-functions at the IP, it is also the largest one at the PC. Indeed, the contribution of the PC to the total beam-beam parameter is largest[1] for $\xi_{y,+}$.

(2) Generally speaking, when looking at the set of all cases "A" ($\xi_0 = 0.03$) and the set of all cases "B" ($\xi_0 = 0.05$), one observes an approximate universality: all curves "A" are roughly similar, with a threshold for the onset of substantial beam blowup occurring at $d/\sigma_{0x,+} \lesssim 6$; similarly, all curves "B" are roughly similar, with substantial beam blowup occurring at $d/\sigma_{0x,+} \lesssim 7.5$. The asymptotic ($d \to \infty$) vertical blowup factor for the LEB is ~15–30% for cases "A" and ~50% for cases "B." When comparing different working points (see plots in the CDR), one sees that the blowup threshold values and the asymptotic blowup factors are tune-dependent. The universality conjecture one might draw from this is the following: the beam blowup curves depend on the β^*'s, working point, beam-beam parameter, synchrotron tune, energy spread and bunch length, but they do not depend on

nominal luminosity, damping times or bunch current as long as the previous parameters are kept fixed. We are unaware of any underpinnings of this universality, if any indeed exists; so far, this is a purely empirical and approximate observation from our set of simulation results, for a very limited set of parameters. In particular, the conjectured dependence of the scaling rules on the LER damping time is the weakest, since we have only one point (strong-strong simulation in case 5A).

(3) The new working point, just above the half-integer, leads to a wider safety margin than the old working point, just above the integer, that was used in the CDR calculations. However, the amount of beam blowup is about the same as in the old working point.

(4) Among the cases we have studied, the largest degree of reliability (the least amount of beam blowup, and the least effect from the PCs) is achieved in case 3A, in which the bunches have their nominal emittance and number of particles, but their spacing is $s_B = 3\lambda_{RF} = 1.89$ m rather than the nominal $s_B = 2\lambda_{RF} = 1.26$ m. Of course, the price to pay is a 33% reduction in luminosity, which in this case would be $\mathscr{L}{\sim}1.9 \times 10^{33}$ cm^{-2} s^{-1}.

(5) For a luminosity close to the nominal target of 3×10^{33} cm^{-2} s^{-1}, it is more reliable to operate at $s_B = 3\lambda_{RF} = 1.89$ m (case 2A2) rather than the nominal $s_B = 2\lambda_{RF} = 1.26$ m (case 1A). The price to pay is a 50% increase in the bunch current and in the nominal emittances over the nominal specifications (the total beam current, however, remains unchanged). However, both cases 1A and 2A2 have comparable amounts of beam blowup, yielding a dynamical value for the luminosity of $\mathscr{L} \sim 2.6 \times 10^{33}$ cm^{-2} s^{-1}.

(6) If a higher-than-nominal luminosity is desired, once again it is safer to operate at $s_B = 3\lambda_{RF} = 1.89$ m with nominal emittances but with bunch currents 67% larger than nominal (case 3B), rather than at $s_B = 2\lambda_{RF} = 1.26$ m with 50% larger-than-nominal emittances and 50% larger-than-nominal bunch currents (case 1B). However, case 3B yields $\mathscr{L} \sim 4.4 \times 10^{33}$ cm^{-2} s^{-1}, while case 1B yields $\mathscr{L} \sim 5.3 \times 10^{33}$ cm^{-2} s^{-1}. Another possibility for larger-than-nominal luminosity is case 2B (with $s_B = 3\lambda_{RF} = 1.89$ m), which yields an even higher value $\mathscr{L} \sim 6.5 \times 10^{33}$ cm^{-2} s^{-1}, but the price to pay is 50% larger-than-nominal emittances plus bunch currents that are a factor of 5/2 times nominal ($3/2 \times 5/3 = 5/2$), along with lessened reliability.

(7) Not surprisingly, simulations with $\tau_+ = 5014$ turns yield similar results to those with $\tau_+ = 4400$ turns.

(8) A simulation for $\xi_0 = 0.03$ with $\tau_+ = 10028$ turns and $\tau_- = 5014$ turns yields similar results to the nominal case with $\tau_+ = \tau_- = 5{,}014$ turns. However, this result is based on a weak-strong simulation with a strong-strong spot-check, and needs to be confirmed further.

(9) Simulations that run for 5 damping times with 5 slices yield similar results to those that run for 3 damping times with 3 slices, at least for $\xi_0 = 0.03$.

6. Acknowledgements

We thank M. Zisman for valuable discussions.

7. References

1. *An Asymmetric B Factory Based on PEP: Conceptual Design Report,* LBL PUB-5303/SLAC-372/CALT-68-1715/UCRL-ID-106426/UC-IIRPA-91-01, Feb. 1991.

2. *PEP-II: An Asymmetric B Factory Design Update*, Feb. 1992.

3. J. L. Tennyson, undocumented code "TRS," 1989.

4. A. Garren *et al*, "An Asymmetric B-Meson Factory at PEP," Proc. 1989 Particle Accelerator Conference, Chicago, March 1989, p. 1847; Y. H. Chin, "Symmetrization of the Beam-beam Interaction," in *Beam Dynamics issues of High luminosity Asymmetric Collider Rings*, Ed. Andrew M. Sessler, AIP Conference Proceedings **214**, 424 (1990); Y. H. Chin, "Beam-Beam Interaction in an Asymmetric Collider for B-Physics," LBL-27665, August, 1989, presented at the XIV Intl. Conf. on High Energy Accelerators, Tsukuba, Japan, August 1989; M. A. Furman, "Luminosity Formulas for Asymmetric Colliders with Beam Symmetries," ABC-25/ESG-0163, Feb. 1991 (rev. Sept. 1991).

5. M. Bassetti and G. A. Erskine, "Closed Expression for the Electrical Field of a Two-Dimensional Gaussian Charge," CERN-ISR-TH/80-06.

6. S. Krishnagopal and R. Siemann, in *Beam Dynamics Issues of High luminosity Asymmetric Collider Rings*, A. M. Sessler, ed., AIP Conf. Proc. **214**, 278 (1990), and *Phys. Rev*. **D41**, 2312 (1990).

TABLE 1A – PRIMARY PARAMETERS

Nominal CDR case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)	HER (e^-)
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	3.878×10^{10}
ε_{0x} [nm-rad]	91.86	45.93
ε_{0y} [nm-rad]	3.675	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.425	7.425
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 1A – IP AND PC PARAMETERS

Nominal CDR case; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)		HER (e^-)	
Δs [cm]	62.9816			
d [mm]	2.82			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1643	0	0.1111
$\Delta\nu_y$	0	0.2462	0	0.2424
β_x [m]	0.375	1.51	0.750	1.30
β_y [m]	0.015	25.23	0.030	13.01
α_x	0	–2.42	0	–1.06
α_y	0	–29.25	0	–18.74
σ_{0x} [μm]	185.6	372.4	185.6	244.4
σ_{0y} [μm]	7.425	304.5	7.425	154.6
$\sigma_{0x'}$ [mrad]	0.495	0.646	0.247	0.274
$\sigma_{0y'}$ [mrad]	0.495	0.353	0.247	0.223
d/σ_{0x}	0	7.572	0	11.541
ξ_{0x}	0.03	–0.000544	0.03	–0.000234
ξ_{0y}	0.03	+0.009096	0.03	+0.002345

TABLE 1B – PRIMARY PARAMETERS

CDR lattice but higher N; $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)	HER (e^-)
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	8.33×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.2596	1.2596
f_c [MHz]	238.000	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	9.383×10^{10}	6.463×10^{10}
ε_{0x} [nm-rad]	91.86	45.93
ε_{0y} [nm-rad]	3.675	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.425	7.425
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 1B – IP AND PC PARAMETERS

CDR lattice but higher N; $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)		HER (e^-)	
Δs [cm]	62.9816			
d [mm]	2.82			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1643	0	0.1111
$\Delta\nu_y$	0	0.2462	0	0.2424
β_x [m]	0.375	1.51	0.750	1.30
β_y [m]	0.015	25.23	0.030	13.01
α_x	0	–2.42	0	–1.06
α_y	0	–29.25	0	–18.74
σ_{0x} [μm]	185.6	372.4	185.6	244.4
σ_{0y} [μm]	7.425	304.5	7.425	154.6
$\sigma_{0x'}$ [mrad]	0.495	0.646	0.247	0.274
$\sigma_{0y'}$ [mrad]	0.495	0.353	0.247	0.223
d/σ_{0x}	0	7.572	0	11.541
ξ_{0x}	0.05	–0.000907	0.05	–0.000391
ξ_{0y}	0.05	+0.015160	0.05	+0.003909

TABLE 2A – PRIMARY PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; $\mathcal{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	3×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.8894	1.8894
f_c [MHz]	158.667	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.0	476.0
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	8.445×10^{10}	5.817×10^{10}
ε_{0x} [nm-rad]	137.8	68.90
ε_{0y} [nm-rad]	5.513	2.757
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [µm]	227.3	227.3
σ^*_{0y} [µm]	9.094	9.094
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 2A – IP AND PC PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; $\mathscr{L}_0 = 3 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)		HER (e^-)	
Δs [cm]	94.47			
d [mm]	7.41			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1844	0	0.1403
$\Delta\nu_y$	0	0.2478	0	0.2453
β_x [m]	0.375	4.74	0.750	2.41
β_y [m]	0.015	32.65	0.030	24.49
α_x	0	–9.20	0	–2.60
α_y	0	8.68	0	–15.95
σ_{0x} [µm]	227.3	808.2	227.3	407.5
σ_{0y} [µm]	9.094	424.3	9.094	259.8
$\sigma_{0x'}$ [mrad]	0.606	1.578	0.303	0.471
$\sigma_{0y'}$ [mrad]	0.606	0.114	0.303	0.170
d/σ_{0x}	0	9.169	0	18.185
ξ_{0x}	0.03	–0.000371	0.03	–0.000094
ξ_{0y}	0.03	+0.002557	0.03	+0.000959

TABLE 2B – PRIMARY PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; $\mathscr{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)	HER (e^-)
$\mathscr{L}_0$ [cm^{-2} s^{-1}]	8.33×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.8894	1.8894
f_c [MHz]	158.667	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	14.075×10^{10}	9.695×10^{10}
ε_{0x} [nm-rad]	137.8	68.90
ε_{0y} [nm-rad]	5.513	2.757
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	227.3	227.3
σ^*_{0y} [μm]	9.094	9.094
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 2B – IP AND PC PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; $\mathcal{L}_0 = 8.33 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)		HER (e^-)	
Δs [cm]	94.47			
d [mm]	7.41			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1844	0	0.1403
$\Delta\nu_y$	0	0.2478	0	0.2453
β_x [m]	0.375	4.74	0.750	2.41
β_y [m]	0.015	32.65	0.030	24.49
α_x	0	–9.20	0	–2.60
α_y	0	8.68	0	–15.95
σ_{0x} [μm]	227.3	808.2	227.3	407.5
σ_{0y} [μm]	9.094	424.3	9.094	259.8
$\sigma_{0x'}$ [mrad]	0.606	1.578	0.303	0.471
$\sigma_{0y'}$ [mrad]	0.606	0.114	0.303	0.170
d/σ_{0x}	0	9.169	0	18.185
ξ_{0x}	0.05	–0.000619	0.05	–0.000157
ξ_{0y}	0.05	+0.004262	0.05	+0.001599

TABLE 3A – PRIMARY PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; N, ε_0 = nominal; $\mathcal{L}_0 = 2 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	2×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.8894	1.8894
f_c [MHz]	158.667	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	5.630×10^{10}	3.878×10^{10}
ε_{0x} [nm-rad]	91.86	45.93
ε_{0y} [nm-rad]	3.675	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [μm]	185.6	185.6
σ^*_{0y} [μm]	7.425	7.425
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 3A – IP AND PC PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; N, ε_0 = nominal; $\mathscr{L}_0 = 2 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.03

	LER (e^+)		HER (e^-)	
Δs [cm]	94.47			
d [mm]	7.41			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1844	0	0.1403
$\Delta\nu_y$	0	0.2478	0	0.2453
β_x [m]	0.375	4.74	0.750	2.41
β_y [m]	0.015	32.65	0.030	24.49
α_x	0	–9.20	0	–2.60
α_y	0	8.68	0	–15.95
σ_{0x} [μm]	185.6	659.9	185.6	332.7
σ_{0y} [μm]	7.425	346.4	7.425	212.1
$\sigma_{0x'}$ [mrad]	0.495	1.288	0.247	0.385
$\sigma_{0y'}$ [mrad]	0.495	0.093	0.247	0.138
d/σ_{0x}	0	11.23	0	22.27
ξ_{0x}	0.03	–0.000247	0.03	–0.000063
ξ_{0y}	0.03	+0.001705	0.03	+0.000639

TABLE 3B – PRIMARY PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; ε_0 = nominal; $\mathcal{L}_0 = 5.56 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)	HER (e^-)
$\mathcal{L}_0$ [cm^{-2} s^{-1}]	5.56×10^{33}	
C [m]	2,200	2,200
E [GeV]	3.1	9.0
s_B [m]	1.8894	1.8894
f_c [MHz]	158.667	
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.000	476.000
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_ℓ [cm]	1.0	1.0
σ_E/E	1.00×10^{-3}	0.616×10^{-3}
N	9.383×10^{10}	6.463×10^{10}
ε_{0x} [nm-rad]	91.86	45.93
ε_{0y} [nm-rad]	3.675	1.838
β^*_x [m]	0.375	0.750
β^*_y [m]	0.015	0.030
σ^*_{0x} [µm]	185.6	185.6
σ^*_{0y} [µm]	7.425	7.425
τ_x [turns]	4,400	5,014
τ_y [turns]	4,400	5,014

TABLE 3B – IP AND PC PARAMETERS

$s_B = 3\lambda_{RF} = 1.8894$ m; ε_0 = nominal; $\mathscr{L}_0 = 5.56 \times 10^{33}$ cm^{-2} s^{-1}; ξ_0=0.05

	LER (e^+)		HER (e^-)	
Δs [cm]	94.47			
d [mm]	7.41			
	IP	1st PC	IP	1st PC
$\Delta\nu_x$	0	0.1844	0	0.1403
$\Delta\nu_y$	0	0.2478	0	0.2453
β_x [m]	0.375	4.74	0.750	2.41
β_y [m]	0.015	32.65	0.030	24.49
α_x	0	–9.20	0	–2.60
α_y	0	8.68	0	–15.95
σ_{0x} [µm]	185.6	659.9	185.6	332.7
σ_{0y} [µm]	7.425	346.4	7.425	212.1
$\sigma_{0x'}$ [mrad]	0.495	1.288	0.247	0.385
$\sigma_{0y'}$ [mrad]	0.495	0.093	0.247	0.138
d/σ_{0x}	0	11.23	0	22.27
ξ_{0x}	0.05	–0.000412	0.05	–0.000105
ξ_{0y}	0.05	+0.002841	0.05	+0.001066